

Next Generation OpenGGCM

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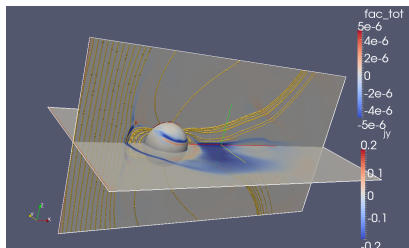
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Outline

- 1 Next Generation OpenGGCM
 - Deliverable
 - Status
 - Interactions with CCMC
- 2 Recent / ongoing work
- 3 OpenGGCM Development
 - Github
 - Multi-fluid simulations of Ganymede
 - Blending multi-fluid and MHD
- 4 Summary

Our deliverable

Next generation OpenGGCM



- Options for fluid plasma models (MHD, Hall-MHD, multi-fluid, pressure tensor closures)
- Adaptive mesh refinement
- Implicit time integration
- Coupled to CTIM (done), IPE (in progress), RCM (done).

New components available as open source (LGPL), whole model to be delivered to CCMC.

solar wind b.c.	ionosphere b.c.	CTIM	RCM	openggcm	
reconstruct	Riemann	divB	MHD	gkeyll	libmrc/mhd
multi-d fields	domain decomp	mesh refinement	I/O	libmrc/base	

Status

Progress on OpenGGCM

- Modularization using LIBMRC
- Checkpointing, parallel I/O
- Hall-MHD
- (Adaptive) mesh refinement: flux correction, E field correction ($\nabla \cdot B = 0$), parallel sparse matrix multiply
- New options for MHD/Hall-MHD: cell-centered with div B cleaning (8-wave, GLM).
- Inner b.c. on reconstructed states at boundary face.
- Coupling with GKEYLL 5-moment and 10-moment multi-fluid models, incl. solar wind and ionosphere b.c.
- Visualization tools (python/viscid, paraview)
- Software development on github, automated testing
- Blending MHD / multi-fluid solutions

CCMC

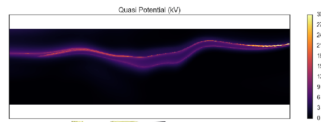
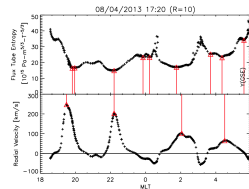
OpenGGCM facts

- OpenGGCM has been community model at CCMC since 2001. 2011-2015: 365 runs on demand
 - Number of papers that include OpenGGCM results approaching 100.
 - Current version 4.0 delivered in 2011.
-
- Multi-fluid asymmetric reconnection data delivered to CCMC, available online.
 - OpenGGCM v5 delivery planned for end of this summer:
 - two-way coupling with RCM
 - static mesh refinement
 - (parallel) I/O improvements
 - flexibility to simulate systems other than Earth
 - various new MHD / Hall-MHD solvers
 - coupling with gkeyll provides multi-fluid capabilities

Only mature features will be made available for runs-on-request.

Recent / ongoing work

- Plasma Sheet Injections into the Inner Magnetosphere: Two-Way Coupled OpenGGCM-RCM Model Results
- Analyzing multiple reconnection sites during FTE formation using the quasi potential.
- Wave propagation in the magnetosphere



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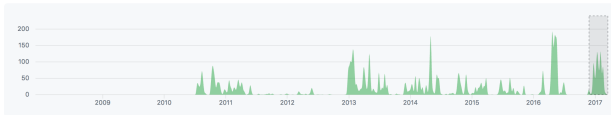
OpenGCM Development

- Now hosted on github.
- Activity:

Jan 2, 2017 – Apr 24, 2017

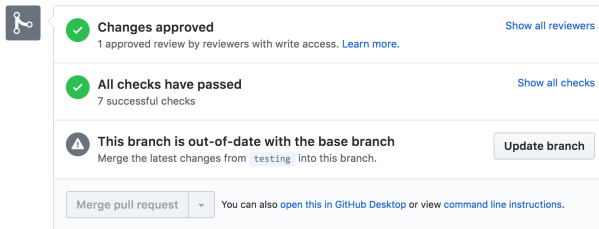
Contributions to testing, excluding merge commits

Contributions: **Commits** ▾



OpenGGCM Development

- “Pull requests” to merge new features and bug fixes; with review and automated testing



- Issue tracker: 24 open / 8 closed
- 27 PRs merged (flexible units; consolidate b.c. / i.c. for gkeyll / mhd, automated testing, gkeyll ionosphere coupling, many fixes + cleanup)

3D multi-fluid simulations of Ganymede

- Ganymede's dipole interacting with southward Jovian magnetic field
- Uses realistic ion mass but artificial electron mass and speed of light
- Correctly captures Alfvén wings due to sub-sonic sub-Alfvénic inflow boundary condition
- Demonstrates roles of electrons in both local reconnection physics and global convection

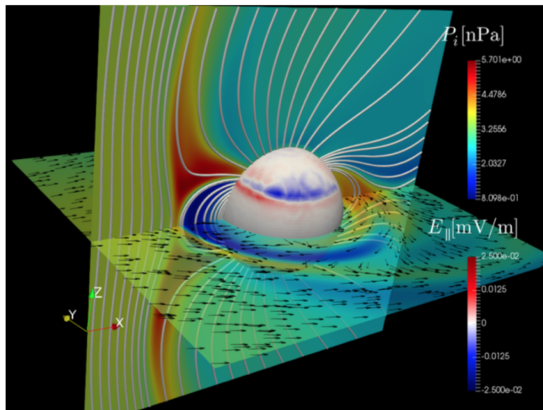


Figure: Snapshot near the Ganymede later in the simulation showing slices of ion pressure, surface parallel electric field, magnetic field lines and ion flow patterns.

Initial and boundary conditions

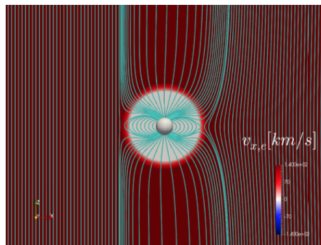
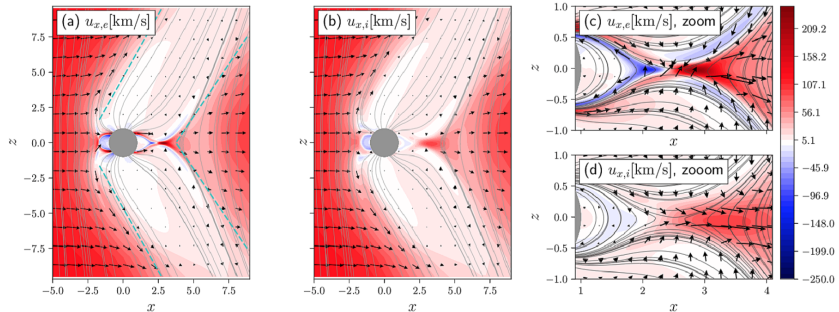


Figure: Initial flow velocity along $+x$ over magnetic field lines in the meridional plane.

- physical domain $[-64, 64]^3$ in unit of R , numerical grid $528 \times 512 \times 512$
- Ganymede is at origin, Jovian plasmas flow in from $-x$
- inflow Jovian: $B \sim (0, -6, -77) \text{ nT}$, $\rho \sim 56 \text{ amu/cm}^3$, $p \sim 3.8 \text{ nPa}$, $v_x \sim 140 \text{ km/s} \Rightarrow M_s \sim 0.56$, $M_A \sim 0.62$
- Ganymede: $R \sim 2634.1 \text{ km}$, surface dipole field $B_0 \sim (-18, 51.8, -716.8) \text{ nT}$

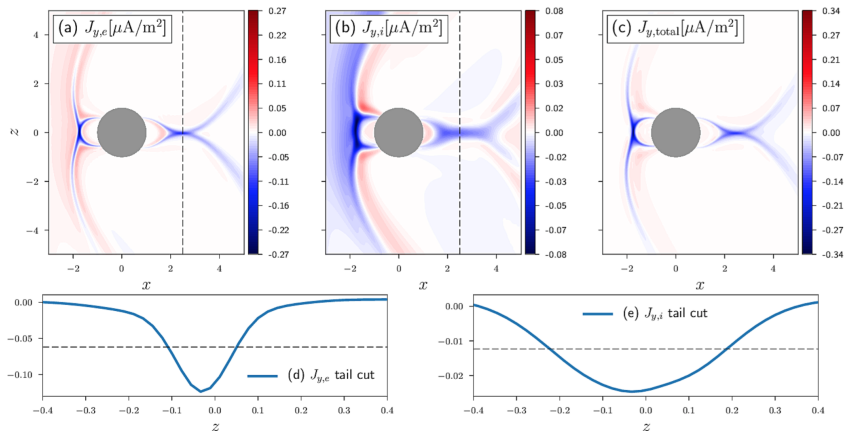
- $d_{i,\text{Jovian}} \sim 0.2R$, $m_i/m_e = 25$, $p_i/p_e = 5$, $c = 6000 \text{ km/s}$, $\Delta x_{\min} \sim d_i/10 \sim d_e/2$
- 10-moment closure, $k_e = 1/d_e$, $k_i = 1/d_i$ updated locally every time step
- fixed values at $-x$; floated values at $+x$, $\pm y$, and $\pm z$
- at radius $= R$, ghost cell values are constant ρ and p , $\rho \mathbf{v}$ radially reversed, \mathbf{B}_1 radially reversed, $\mathbf{E} = 0$
 - no induction layer

Alfven wing structure



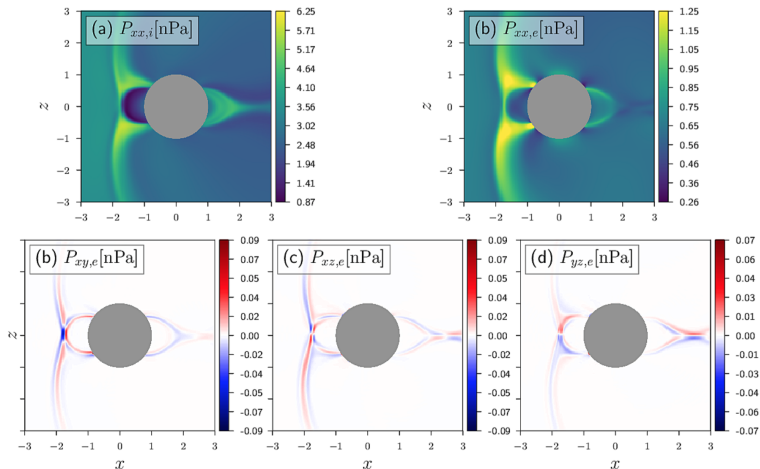
- plasmas slowed down in the wings
- reconnections at leading and trailing side like Earth+south IMF Bz
- separation of electron and ion scales
- fast electron outflow jets driven by reconnection

Reconnection physics 1: ion / electron scales



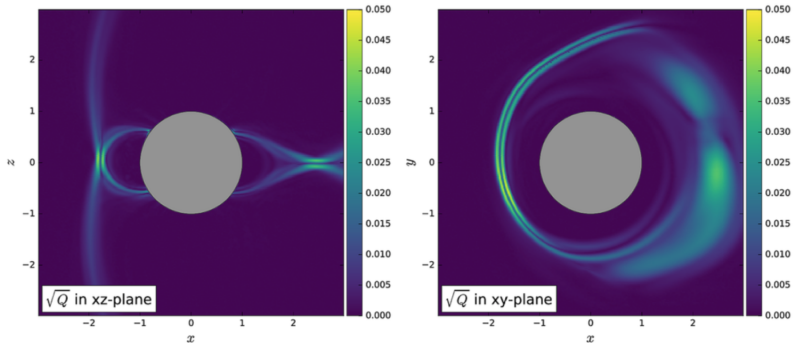
- currents carried mainly by electrons
- $J_{y,e}$ half-thickness $2d_e$; $J_{y,i}$ half-thickness $1d_i$;

Reconnection physics 2: pressure tensor



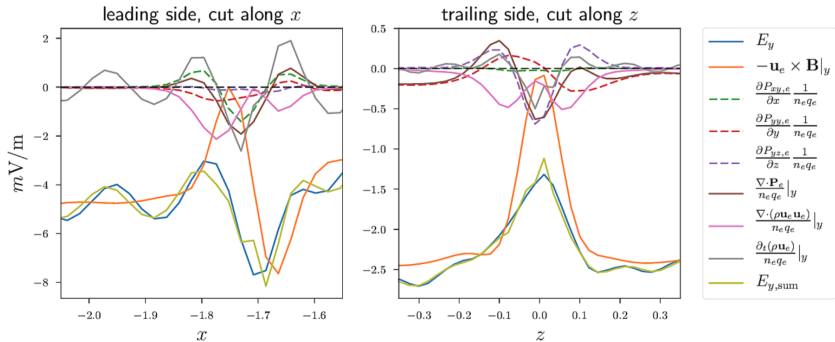
- $P_{xx,e}$ concentration near foot-points
- $\mathbf{P}_{off,e}$ is small in magnitude but highly structured
- $\mathbf{P}_{off,e}$ polarities agree with local 2D PIC/Vlasov studies

Reconnection physics 3: pressure non-gyrotropy

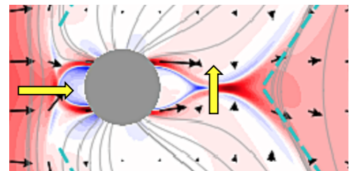


- Electron non-gyrotropy Q as suggested by Swisdak 2016

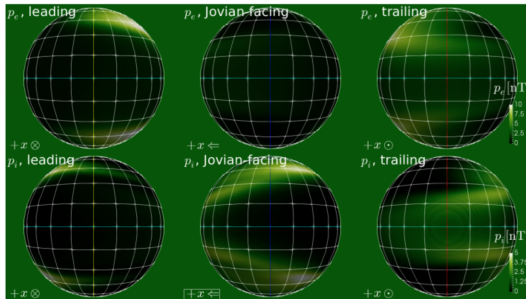
Reconnection physics 4: Ohm's Law decomposition



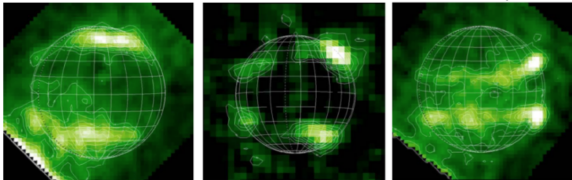
- $\nabla \cdot \mathbf{P}_e$ important on both reconnection sites
 - leading side, $\partial P_{xy}/\partial x$, $\partial P_{yy}/\partial y$
 - trailing side, $\partial P_{yz}/\partial z$, $\partial P_{yy}/\partial y$
- inertia terms also significant



Surface brightness



↑ simulation, pressures ↓ oxygen emission from HST (McGrath2013)



- "brightness" represented by surface pressure, not from rigorous semi-empirical models
- captures some key features of observations
- p_e and p_i show different polarities

Multi-fluid simulations of Earth

- First simulations with Earth parameters and coupled ionosphere look reasonable.

Issues

- Resolution requirements: need to resolve d_i , d_e to give trustworthy results and avoid instability (as opposed to Hall-MHD, which gracefully degrades to MHD). $300 \times 100 \times 100 R_E$ box with $.01 R_E$ resolution: $30000 \times 10000 \times 10000$ grid points...
- Boundary conditions are really only defined in terms of MHD quantities (solar wind, ionosphere potential $\rightarrow E \times B$ velocity, while gkeyll wants ρ , v , p per species, E , B)

\Rightarrow **multi-physics simulation**

Blending multi-fluid and MHD

Basic blending algorithm: time step

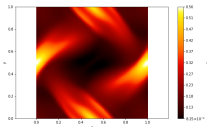
- At beginning of time step: Calculate MHD state from multi-fluid state (uniquely determined).
- Perform gkeyll step to get new gkeyll state.
- Perform MHD step to get new MHD state.
- Calculate new MHD-based multi-fluid state from MHD step result (needs assumptions*).
- Blend new multi-fluid state from gkeyll and MHD-based states depending on time / location:

$$state^{n+1} = \alpha state_{MHD\ based}^{n+1} + (1 - \alpha) state_{gkeyll\ based}^{n+1}$$

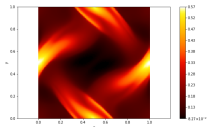
* E from Ohm's Law, v_s from MHD momentum and current, ρ_s from ρ_{MHD} and assumption, p_s from p_{MHD} and assumption.

Blending Orzag-Tang

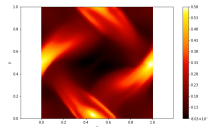
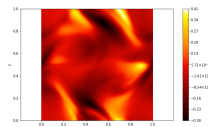
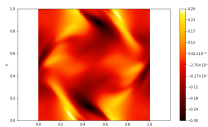
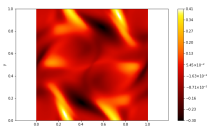
Hall MHD



multi-fluid



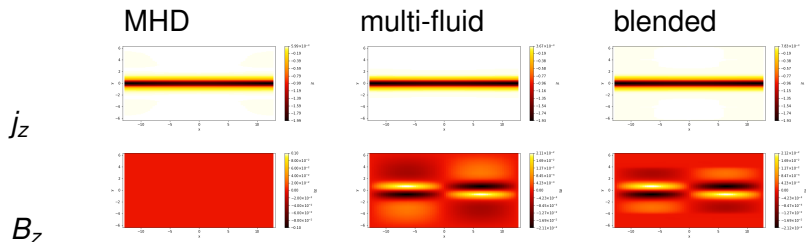
blended

 ρ  B_z

Blended: top half Hall-MHD, bottom half multi-fluid

Blending GEM challenge

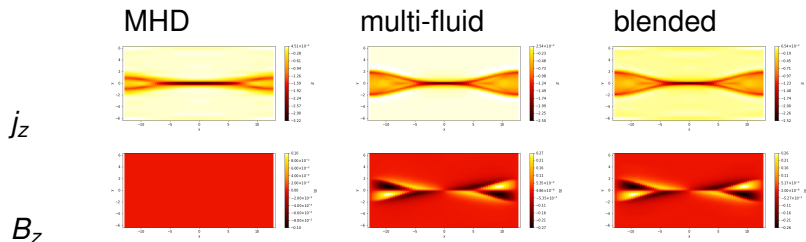
$$t = 1\tau_A$$



Blended: gkeyll for $-4 \leq y \leq 4$, MHD otherwise

Blending GEM challenge

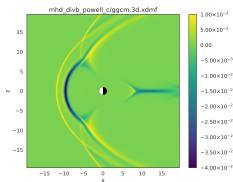
$$t = 20\tau_A$$



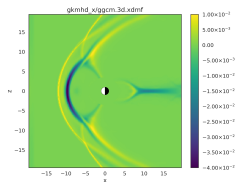
Blended: gkeyll for $-4 \leq y \leq 4$, MHD otherwise

Blending OpenGGCM

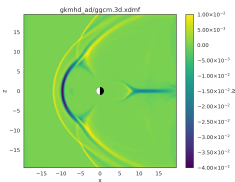
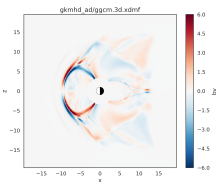
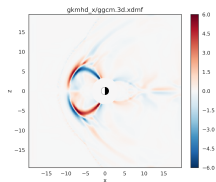
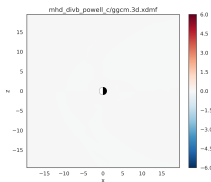
MHD



multi-fluid



blended


 j_y

 B_y

Blended: gkeyll for $r < 13R_E$, MHD otherwise

Summary

- Next Generation OpenGGCM has taken shape
 - Modularized OpenGGCM based on LIBMRC
 - Mesh Refinement
 - Hall term, ATHENA coupling, cell-centered schemes
 - GKEYLL coupling, incl. b.c.s
 - Inner b.c. and parameters for Ganymede
 - Blending MHD and multi-fluid
 - Solid software engineering
 - OpenGGCM v5 push to CCMC this summer, final code drop next summer
- Outlook
 - Production-level blended simulations of Earth
 - Studies of 5-moment and 10-moment closure at Earth
 - Multi-fluid simulations of Mercury

RCM coupling

Cramer et al: **Plasma Sheet Injections into the Inner Magnetosphere: Two-Way Coupled OpenGGCM-RCM Model Results** (submitted to JGR, under revision)

- There is a clear association of plasma sheet injections with bubbles.
- The majority of inward plasma transport in the magnetotail beyond $6.6 R_E$ is due to bubbles, regardless of storm activity.
- The average peak velocity of injections is higher for increasing downtail distances, stronger storms (when compared with storms having similar drivers), and storms driven by CIRs (when compared with CME-driven storms of similar strength).

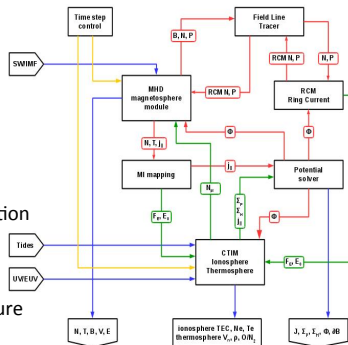
RCM (Rice Convection Model)

- 2-D ionosphere grid representing footpoints of flux tubes
- Solves motion of flux tubes due to potential, induction and drifts
- Main inputs: outer boundary conditions, ionosphere potential

RCM coupling

Model Coupling Methodology

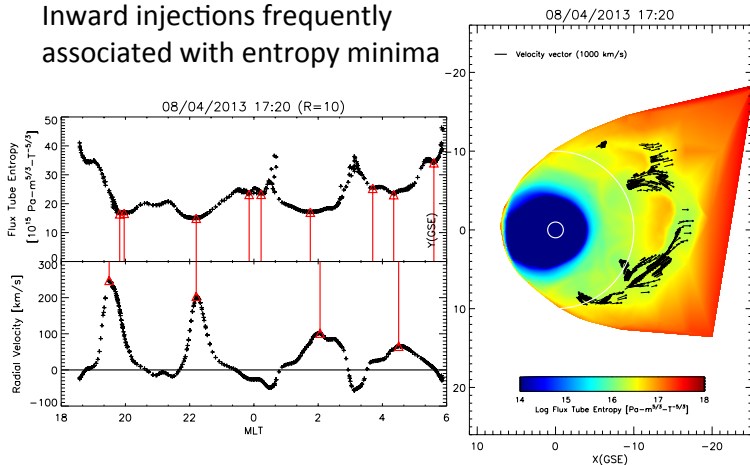
- OpenGGCM -> Ionosphere
 - Sends MHD density, pressure, auroral precipitation, FAC
 - Receives Ionosphere Potential
- RCM -> Ionosphere
 - Receives Ionosphere Potential
 - Sends RCM FACs, auroral precipitation
 - Blends with MHD values
- RCM -> OpenGGCM
 - Convert flux tube content to pressure and density (and vice-versa)
 - Receives MHD pressure, density at boundary
 - Flux tube volume-weighted averages along field line
 - Sends RCM pressure, density
 - Nudge MHD P , n values (RCM influence greater in inner region)
 - RCM feedback slowly ramped up after MHD initialization period



Injections and bubbles

Snapshot of Injections at R=10

Inward injections frequently associated with entropy minima

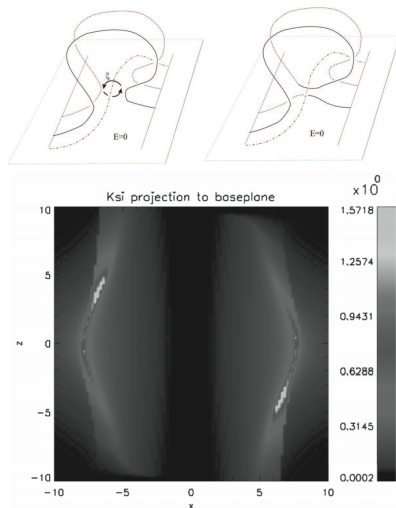


Quasi Potential

In the magnetopause, reconnection is not constrained to only occur at a separator.

Hesse et al (2005) outlined a method to quantify reconnection regardless of topological features using the quasi potential

$$\Xi(\alpha, \beta) = - \int_{\alpha, \beta} \mathbf{E} \cdot d\mathbf{s}$$



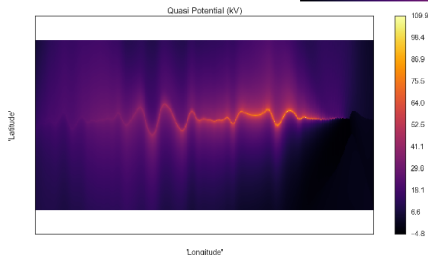
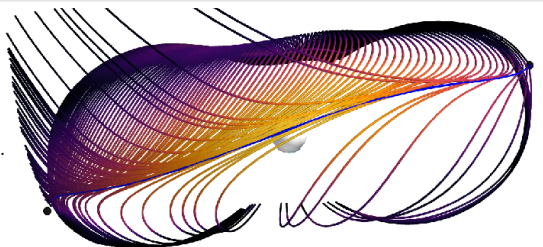
[Hesse et al., 2005]

FTE Formation / multiple reconnection sites

$$\Xi(\alpha, \beta) = - \int_{\alpha, \beta} \mathbf{E} \cdot d\mathbf{s}.$$

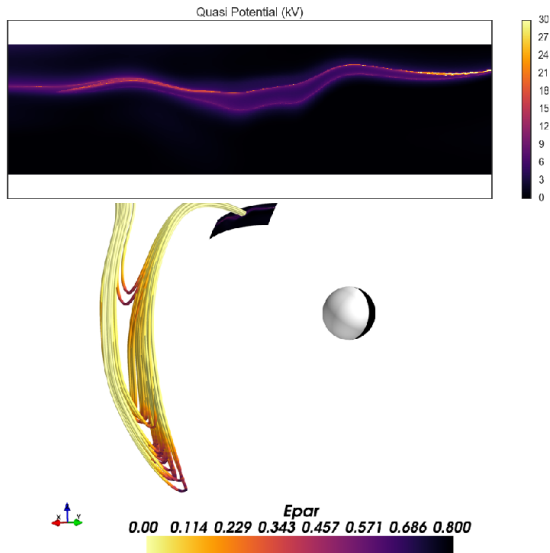
$$R_{\text{global}} = \text{Max}(\Xi)$$

(Hesse et al 2005)



Separator E_{par} 137 kV
 Ξ_{max} 110 kV
CPCP **233 kV**

FTE Formation / multiple reconnection sites



Why study MHD wave travel time?

- Magnetohydrodynamic (MHD) waves carry energy between different regions.
- Play a key role to transport a signal of energy release from the magnetotail to the aurora region during the substorm (Liou et al., 2009).
- It is critical to determine MHD wave travel time and speed in the magnetotail.
- MHD waves can provide remote sensing information about their sources and the regions they pass through.

Wave propagation simulation

from [Ferdousi et al., JGR 2016]

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Wave propagation time results

